

New Results for Ultraperipheral Heavy Ion Collisions

Antoni Szczurek^{1,2,a)}, Mariola Klusek-Gawenda^{1,b)}, Piotr Lebiedowicz^{1,c)} and Wolfgang Schäfer^{1,d)}

¹*Institute of Nuclear Physics Polish Academy of Sciences, Radzikowskiego 152, PL-31-342 Kraków, Poland*

^{a)}Corresponding author: Antoni.Szczurek@ifj.edu.pl

²*Also at University of Rzeszów, PL-35-959 Rzeszów, Poland.*

^{b)}Mariola.Klusek@ifj.edu.pl

^{c)}Piotr.Lebiedowicz@ifj.edu.pl

^{d)}Wolfgang.Schafer@ifj.edu.pl

Abstract. We discuss diphoton semi(exclusive) production in ultraperipheral $PbPb$ collisions at energy of $\sqrt{s_{NN}} = 5.5$ TeV (LHC). The nuclear calculations are based on equivalent photon approximation in the impact parameter space. The cross sections for elementary $\gamma\gamma \rightarrow \gamma\gamma$ subprocess are calculated including three different mechanisms: box diagrams with leptons and quarks in the loops, a VDM-Regge contribution with virtual intermediate hadronic excitations of the photons and the two-gluon exchange contribution (formally three-loops). We got relatively high cross sections in $PbPb$ collisions. This opens a possibility to study the $\gamma\gamma \rightarrow \gamma\gamma$ (quasi)elastic scattering at the LHC. We find that the cross section for elastic $\gamma\gamma$ scattering could be measured in the lead-lead collisions for the diphoton invariant mass up to $W_{\gamma\gamma} \approx 15 - 20$ GeV. We identify region(s) of phase space where the two-gluon exchange contribution becomes important ingredient compared to box and nonperturbative VDM-Regge mechanisms. We discuss also first results concerning production of two e^+e^- pairs in UPCs of heavy ions. We considered only double scattering mechanism.

INTRODUCTION

In classical Maxwell theory photons/waves/wave packets do not interact. In contrast, in quantal theory they can interact via quantal fluctuations. So far only inelastic processes, i.e. production of hadrons or jets via photon-photon fusion could be measured e.g. in e^+e^- collisions or in ultraperipheral collisions (UPC) of heavy-ions. It was realized only recently that ultraperipheral heavy-ions collisions can be also a good place where photon-photon elastic scattering could be tested experimentally [1, 2].

Several studies in UPCs concentrated on the production of one dilepton pair (e^+e^- or $\mu^+\mu^-$). Here we discuss first results obtained recently for production of two pairs.

$AA \rightarrow AA\gamma\gamma$ REACTION

Elementary Cross Section

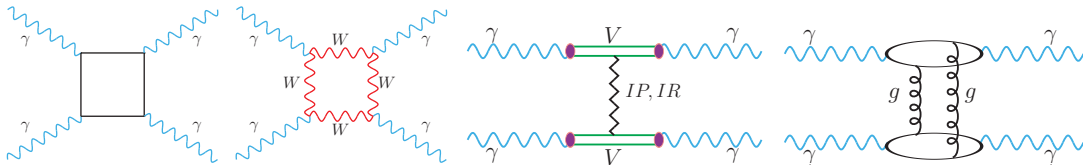


FIGURE 1. Light-by-light scattering mechanisms with the lepton and quark loops (first diagram) and for the intermediate W -boson loop (second diagram). The third diagram represents VDM-Regge mechanism and the last diagram is for two-gluon exchange.

One of the main ingredients of the formula for calculation of the nuclear cross section is elementary $\gamma\gamma \rightarrow \gamma\gamma$ cross section. The lowest order QED mechanisms with elementary particles are shown in two first diagrams of Figure 1. The first diagram is for lepton and quark loops and it dominates at lower photon-photon energies ($W_{\gamma\gamma} < 2m_W$) while the next diagram is for the W (spin-1) boson loops and it dominates at higher photon-photon energies; see [3, 4]. The one-loop box amplitudes were calculated by using the Mathematica package `FormCalc` and the `LoopTools` library. We have obtained good agreement when confronting our results with those in [3, 5, 6]. Including higher-order contributions seems to be interesting. In [6] the authors considered both the QCD and QED corrections (two-loop Feynman diagrams) to the one-loop contributions in the ultrarelativistic limit ($\hat{s}, |\hat{t}|, |\hat{u}| \gg m_f^2$). The corrections are quite small numerically so the leading order computations considered by us are satisfactory. In the last two diagrams of Figure 1 we show processes that are the same order in α_{em} but higher order in α_s . The third diagram presents situation where both photons fluctuate into virtual vector mesons (here we include only different light vector mesons: ρ, ω, ϕ). The last diagram shows two-gluon exchange mechanism which is formally three-loop type. Its contribution to the elastic scattering of photons at high energies has been first considered e.g. in [7]. Indeed in the limit where the Mandelstam variables of the $\gamma\gamma \rightarrow \gamma\gamma$ process satisfy the relation $\hat{s} \gg -\hat{t}, -\hat{u}$, simplifications are possible and the three-loop process becomes tractable. This corresponds to a near-forward, small-angle, scattering of photons. In our treatment, we go beyond the early work [7] by including finite fermion masses, as well as the full momentum structure in the loops, and we consider all helicity amplitudes [8].

Nuclear Cross Section

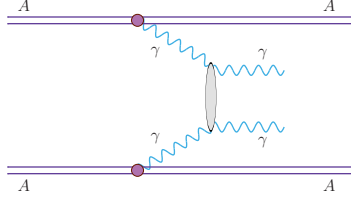


FIGURE 2. Diphoton production in ultrarelativistic UPC of heavy ions.

The general situation for the $AA \rightarrow AA\gamma\gamma$ reaction is sketched in Figure 2. In equivalent photon approximation (EPA) in the impact parameter space, the total (phase space integrated) cross section can be expressed through the five-fold integral (for more details see e.g. [9])

$$\sigma_{A_1 A_2 \rightarrow A_1 A_2 \gamma\gamma}(\sqrt{s_{A_1 A_2}}) = \int \sigma_{\gamma\gamma \rightarrow \gamma\gamma}(W_{\gamma\gamma}) N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) S_{abs}^2(\mathbf{b}) 2\pi b db d\bar{b}_x d\bar{b}_y \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{\gamma\gamma}, \quad (1)$$

where $N(\omega_i, \mathbf{b}_i)$ are photon fluxes, $W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$ and $Y_{\gamma\gamma} = (y_{\gamma_1} + y_{\gamma_2})/2$ is a invariant mass and a rapidity of the outgoing $\gamma\gamma$ system. Energy of photons is expressed through $\omega_{1/2} = W_{\gamma\gamma}/2 \exp(\pm Y_{\gamma\gamma})$. \mathbf{b}_1 and \mathbf{b}_2 are impact parameters of the photon-photon collision point with respect to parent nuclei 1 and 2, respectively, and $\mathbf{b} = \mathbf{b}_1 - \mathbf{b}_2$ is the standard impact parameter for the $A_1 A_2$ collision.

The photon flux ($N(\omega, b)$) is expressed through a nuclear charge form factor. In our calculations we used two different types of the form factor. The first one, called here realistic form factor, is the Fourier transform of the charge distribution in the nucleus and the second is given by a simple analytic form and is called monopole. More details can be found e.g. in [2, 9].

$AA \rightarrow AAe^+e^-e^+e^-$ REACTION

In [14] we have considered for a first time production of two lepton pairs. The cross section for single e^+e^- production is calculated as described in [15] and the method is very similar as explained shortly in the section above. The basic formula can be written differentially in kinematical variables of the produced leptons (rapidities and transverse momenta) as:

$$\frac{d\sigma_{A_1 A_2 \rightarrow A_1 A_2 e^+e^-}}{dy_+ dy_- dp_t} = \int \frac{dP_{\gamma\gamma \rightarrow e^+e^-}(b; y_+, y_-, p_t)}{dy_+ dy_- dp_t} d^2b. \quad (2)$$

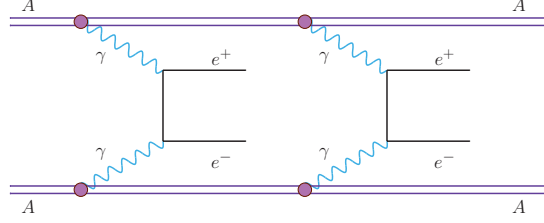


FIGURE 3. Double-scattering mechanism for $e^+e^-e^+e^-$ production in ultrarelativistic UPC of heavy ions.

The double production of two dielectron pairs is shown in Figure 3. The cross section for double scattering can be written as:

$$\frac{d\sigma_{AA \rightarrow AAe^+e^-e^+e^-}}{dy_1 dy_2 dy_3 dy_4} = \frac{1}{2} \int \left(\frac{dP_{\gamma\gamma \rightarrow e^+e^-}(b, y_1, y_2; p_t > p_{t, cut})}{dy_1 dy_2} \times \frac{dP_{\gamma\gamma \rightarrow e^+e^-}(b, y_3, y_4; p_t > p_{t, cut})}{dy_3 dy_4} \right) 2\pi b db. \quad (3)$$

The combinatorial factor $1/2$ takes into account identity of the two lepton pairs.

RESULTS FOR BOTH PROCESSES

Production of Two Photons

In Figure 4 (left panel) we show contributions of the mechanisms presented in Figure 1 for fixed value of energy $W = 10$ GeV. The differential cross section is shown as a function of $z = \cos \theta$, where θ is the scattering angle in the $\gamma\gamma$ cms. The contribution of the VDM-Regge is concentrated at $z \approx \pm 1$. In contrast, the box contribution extends over a broad range of z . The two-gluon exchange contribution occupies intermediate regions of z . We wish to add here, that the approximations made in the calculation of the two-gluon exchange are justified in a small angle region only. At small z the error can be large. In addition, we show the difference between results when we include gluon mass ($m_g = 750$ MeV, solid line) and for massless gluon ($m_g = 0$, dashed line).

The elementary angle-integrated cross section for the box and VDM-Regge contributions is shown in the second panel of Figure 4 as a function of the photon-photon subsystem energy. Lepton and quark amplitudes interfere enhancing the cross section. For instance in the $4 \text{ GeV} < W < 50 \text{ GeV}$ region, neglecting interference effects, the lepton contribution to the box cross section is by a factor 5 bigger than the quark contribution. Interference effects are large and cannot be neglected. At energies $W > 30 \text{ GeV}$ the VDM-Regge cross section becomes larger than that for the box diagrams. The third panel of Figure 4 shows results for nuclear collisions for the case of realistic charge density (red lines) and monopole form factor (blue lines). The cross section obtained with the monopole form factor is somewhat larger. The difference between the results becomes larger for larger values of $M_{\gamma\gamma}$.

To identify both photons we have to generalize Equation (1) by adding extra integration over an additional kinematical parameter related to angular distribution for the subprocess [2]. Figure 5 shows two-dimensional distributions in photon rapidities in the contour representation. The calculation was done at the LHC energy $\sqrt{s_{NN}} = 5.5 \text{ TeV}$. There we imposed cuts on energies of photons in the laboratory frame ($E_\gamma > 3 \text{ GeV}$). Very different distributions are obtained for boxes (left panel) and VDM-Regge (right panel). In both cases the influence of the imposed cuts is significant. In the case of the VDM-Regge contribution we observe as if non-continuous behaviour which is caused by the strong transverse momentum dependence of the elementary cross section (see Figure 4 in [2]) which causes that some regions in the two-dimensional space are almost not populated. Only one half of the $(y_{\gamma_1}, y_{\gamma_2})$ space is shown for the VDM-Regge contribution. The second half can be obtained from the symmetry around the $y_{\gamma_1} = y_{\gamma_2}$ diagonal. Clearly the VDM-Regge contribution occupies regions outside the main detector ($-2.5 < y_{\gamma_1}, y_{\gamma_2} < 2.5$) and extends towards large rapidities. In the case of the VDM-Regge contribution we show much broader range of rapidity than for the box component. We discover that maxima of the cross section associated with the VDM-Regge mechanism are at $|y_{\gamma_1}|, |y_{\gamma_2}| \approx 5$. Unfortunately this is below the limitations of the Zero Degree Calorimeters ($|\eta| > 8.3$ for ATLAS [11] or 8.5 for CMS [12]).

In Figure 6 we show numbers of counts in the 1 GeV intervals expected for assumed integrated luminosity: $L_{int} = 1 \text{ nb}^{-1}$ typical for UPC at the LHC. We have imposed cuts on photon-photon energy and (pseudo)rapidities of both photons. It looks that one can measure invariant mass distribution up to $M_{\gamma\gamma} \approx 15 \text{ GeV}$.

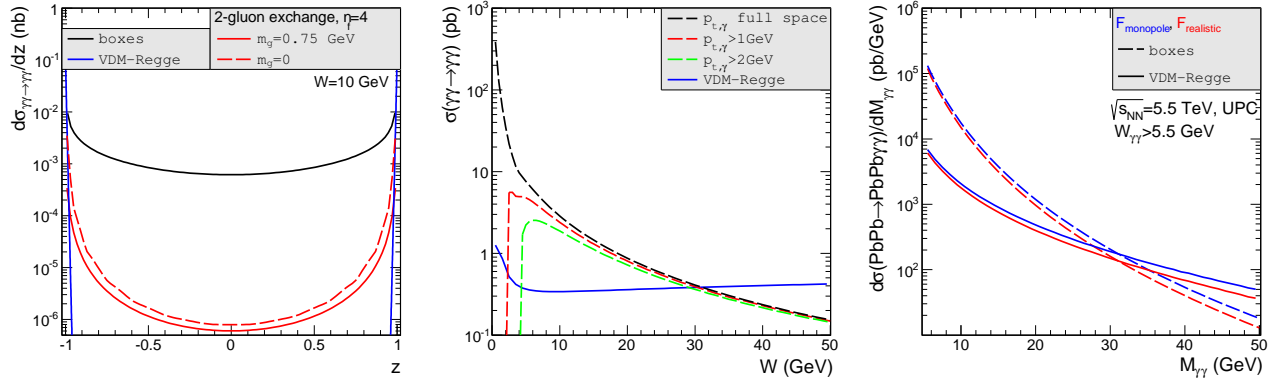


FIGURE 4. Left panel: differential distributions for the light-by-light scattering for $W = 10$ GeV. Middle panel: integrated elementary $\gamma\gamma \rightarrow \gamma\gamma$ cross section as a function of the diphoton energy. The dashed lines show the results for the case when only box contributions (fermion loops) are included and the solid lines show the results for the VDM-Regge mechanism. Right panel: differential nuclear cross section as a function of $\gamma\gamma$ invariant mass at $\sqrt{s_{NN}} = 5.5$ TeV. The distributions with the realistic charge density are depicted by the red (lower) lines and the distributions with the monopole form factor are shown by the blue (upper) lines.

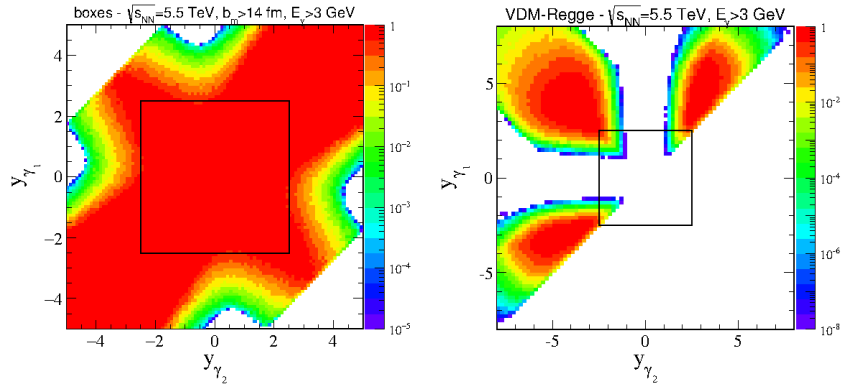


FIGURE 5. Contour representation of two-dimensional ($d\sigma/dy_{\gamma_1} dy_{\gamma_2}$ in nb) distribution in rapidities of the two photons in the laboratory frame for box (left panel) and VDM-Regge (right panel) contributions. Calculations are done for $\sqrt{s_{NN}} = 5.5$ TeV.

Production of Two Lepton Pairs

In Figure 7 our results for e^+e^- production are compared with recent ALICE data [16]. Here we consider lead-lead UPC at $\sqrt{s_{NN}} = 2.76$ TeV with $|y_e| < 0.9$. The left panel shows the ALICE data [16] for $2.2 \text{ GeV} < M_{ee} < 2.6 \text{ GeV}$ and the right panel shows their results for $3.7 \text{ GeV} < M_{ee} < 10 \text{ GeV}$. Our results for single pair production mechanism almost coincide with the experimental data.

Having shown that our approach allows to describe single pair production we can go to our predictions for two e^+e^- pair production. In Table 1 we have collected integrated cross sections for different experimental cuts corresponding to ALICE and ATLAS or CMS experiments.

The numbers presented in the table suggest that the production of two lepton pairs may be possible already at the LHC. In [14] we have discussed also several differential distributions.

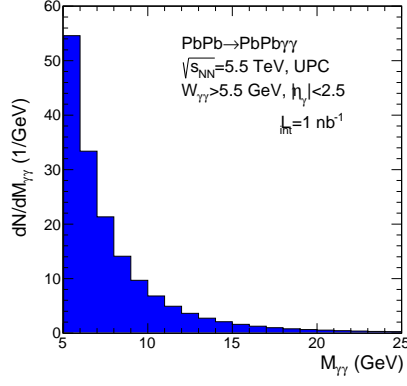


FIGURE 6. Distribution of expected number of counts in 1 GeV bins for cuts on $W_{\gamma\gamma} > 5.5$ GeV and $\eta_\gamma < 2.5$.

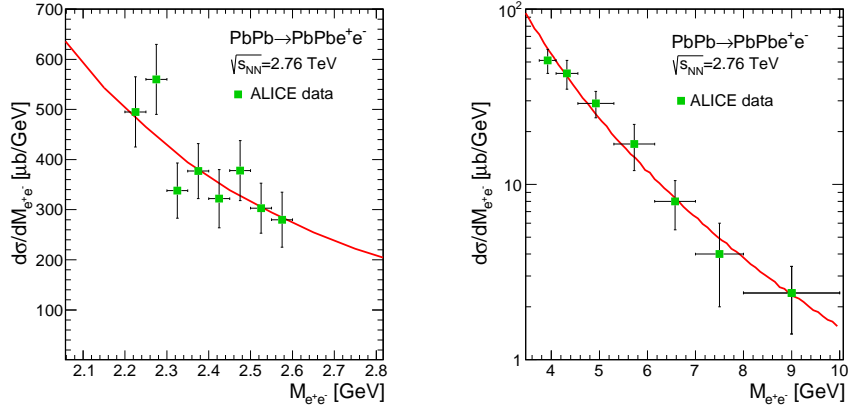


FIGURE 7. Invariant mass distributions of dielectrons in UPC of heavy ions calculated within our approach [15] together with the recent ALICE data [16].

TABLE 1. Nuclear cross section for $PbPb \rightarrow PbPbe^+e^-e^+e^-$ at $\sqrt{s_{NN}} = 5.5$ TeV for different cuts specified in the table.

cut set	σ_{UPC}	Nevents for $L=1 \text{ nb}^{-1}$
$p_{t_e} > 0.2 \text{ GeV}$	$52.525 \mu\text{b}$	52 525
$p_{t_e} > 0.2 \text{ GeV}, y_e < 2.5$	$10.636 \mu\text{b}$	10 636
$p_{t_e} > 0.2 \text{ GeV}, y_e < 1$	$0.649 \mu\text{b}$	649
$p_{t_e} > 0.3 \text{ GeV}, y_e < 4.9$	$7.447 \mu\text{b}$	7 447
$p_{t_e} > 0.3 \text{ GeV}, y_e < 2.5$	$2.052 \mu\text{b}$	2 052
$p_{t_e} > 0.5 \text{ GeV}, y_e < 4.9$	$0.704 \mu\text{b}$	704
$p_{t_e} > 0.5 \text{ GeV}, y_e < 2.5$	$0.235 \mu\text{b}$	235
$p_{t_e} > 1 \text{ GeV}$	25.2 nb	25
$p_{t_e} > 1 \text{ GeV}, y_e < 4.9$	22.6 nb	23
$p_{t_e} > 1 \text{ GeV}, y_e < 2.5$	9.8 nb	10
$p_{t_e} > 1 \text{ GeV}, y_e < 1$	0.6 nb	1

SUMMARY

In our recent papers [2, 8] we have studied in detail how to measure elastic photon-photon scattering in ultrarelativistic ultraperipheral lead-lead collisions. The nuclear calculations were performed in an equivalent photon approximation in the impact parameter space. The cross section for photon-photon scattering was calculated taking into account well known box diagrams with elementary standard model particles (leptons and quarks), a VDM-Regge component which was considered only recently [2] in the context of $\gamma\gamma \rightarrow \gamma\gamma$ scattering as well as a two-gluon exchange, including massive quarks, all helicity configurations of photons and massive and massless gluon. Several distributions in different kinematical variables were calculated. For $AA \rightarrow AA\gamma\gamma$ reactions we identified regions of the phase space where the two-gluon contribution should be enhanced relatively to the box contribution. The region of large rapidity difference between the two emitted photons and intermediate transverse momenta $1 \text{ GeV} < p_t < 2 - 5 \text{ GeV}$ seems optimal in this respect.

Using the monopole form factor we get similar cross section to that found in [1] (after the correction given in Erratum of [1]).

We have shown an estimate of the counting rate for expected integrated luminosity. We expect non-zero counts for subprocess energies smaller than $W_{\gamma\gamma} \approx 15\text{-}20 \text{ GeV}$.

Recently, the ATLAS Collaboration published a note [13] about evidence for light-by-light scattering signatures in quasi-real photon interactions from ultraperipheral lead-lead collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$. The data set was recorded in 2015. The measured fiducial cross section which includes limitation on photon transverse momentum, photon pseudorapidity, diphoton invariant mass, diphoton transverse momentum and diphoton acoplanarity, has been measured to be $70 \pm 20 \text{ (stat.)} \pm 17 \text{ (syst.) nb}$, which is compatible with the value of $49 \pm 10 \text{ nb}$ predicted by us for the ATLAS cuts.

Before presenting our results for $e^+e^-e^+e^-$ production we have shown that our approach describes the production of a single e^+e^- pair. A good agreement with the ALICE invariant mass distribution has been obtained.

Even imposing experimental cuts relevant for different experiments we obtain cross sections that could be measured at the LHC even with relatively low luminosity required for UPC of heavy ions of the order of 1 nb^{-1} . For instance, assuming the integrated luminosity of 1 nb^{-1} for the main ATLAS detector angular coverage and transverse momentum cut on each electron/positron $p_t > 0.5 \text{ GeV}$ we predict 235 events.

In our recent paper we considered only double scattering mechanism. Single scattering mechanism of two lepton pairs is more complicated and will be discussed elsewhere.

ACKNOWLEDGMENTS

This work was partially supported by the Polish National Science Centre grant DEC-2014/15/B/ST2/02528.

REFERENCES

- [1] D. d’Enterria and G. G. da Silveira, Phys. Rev. Lett. **111** (2013) 080405, Erratum: Phys. Rev. Lett. **116** (2016) 129901.
- [2] M. Kłusek-Gawenda, P. Lebiedowicz and A. Szczurek, Phys. Rev. **C93** (2016) 044907.
- [3] D. Bardin, L. Kalinovskaya and E. Uglov, Phys. Atom. Nucl. **73** (2010) 1878.
- [4] P. Lebiedowicz, R. Pasechnik and A. Szczurek, Nucl. Phys. **B881** (2014) 288.
- [5] G. Jikia and A. Tkabladze, Phys. Lett. **B323** (1994) 453.
- [6] Z. Bern, A. De Freitas, L. J. Dixon, A. Ghinculov and H. L. Wong, J. High Energy Phys. **11** (2001) 031.
- [7] I. F. Ginzburg, S. L. Panfil and V. G. Serbo, Nucl. Phys. **B284** (1987) 685.
- [8] M. Kłusek-Gawenda, W. Schäfer and A. Szczurek, Phys. Lett. **B761** (2016) 399.
- [9] M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. **C82** (2010) 014904.
- [10] M. Drees and D. Zeppenfeld, Phys. Rev. **D39** (1989) 2536.
- [11] P. Jenni, M. Nessi and M. Nordberg, Report No. LHCC-I-016, CERN-LHCC-2007-001.
- [12] O. A. Grachov *et al.* (CMS Collaboration), J. Phys. Conf. Ser. **160** (2009) 012059.
- [13] (ATLAS Collaboration), Report No. ATLAS-CONF-2016-111.
- [14] M. Kłusek-Gawenda and A. Szczurek, Phys. Lett. **B763** (2016) 416.
- [15] M. Kłusek-Gawenda and A. Szczurek, Phys. Rev. **C82** (2010) 014904.
- [16] E. Abbas *et al.* (ALICE Collaboration), Eur.Phys.J. **C73** (2013) 2617.